Single-shot picosecond optical damage in Si, Ge and sapphire at 5 μm

R. Agustsson, A. Murokh*, A. Ovodenko, R. Tilton;
RadiaBeam Technologies, LLC.
E. Arab, B. O'Shea, J. Rosenzweig, *UCLA*
I. Pogorelsky, V. Solovyov, *BNL*

Outline

- Introduction to short pulse regime of optical breakdown (OBD)
- GALAXIE project and importance of mid-IR DLA
- 5 μm optical BD studies
- Results

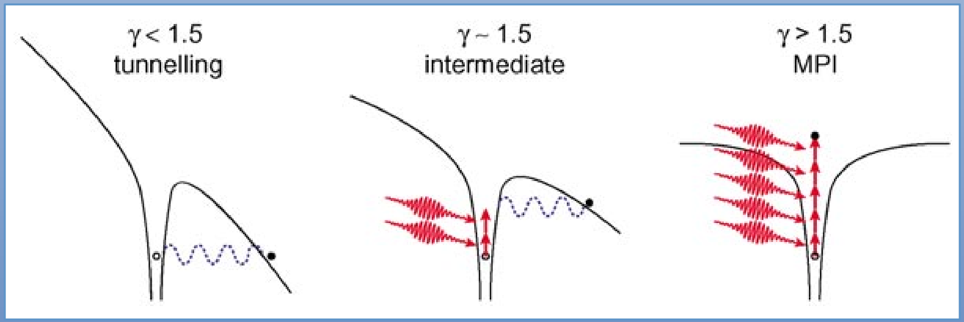
Ionization mechanisms

- Photoionization has band gap dependence (multiphoton ionization vs. tunneling), described by the Keldysh theory

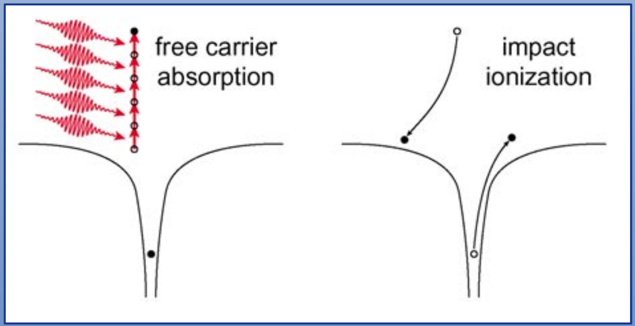
$$\gamma_K = \frac{1}{\lambda}\sqrt{\frac{cE_g}{r_e I}}$$

- Avalanche ionization is exponential and dominates ionization for long pulses

C.B. Schaffer, A. Brodeur and E. Mazur, *Meas. Sci. Technol.* **12** (2001) 1784–1794



photoionization



avalanche ionization

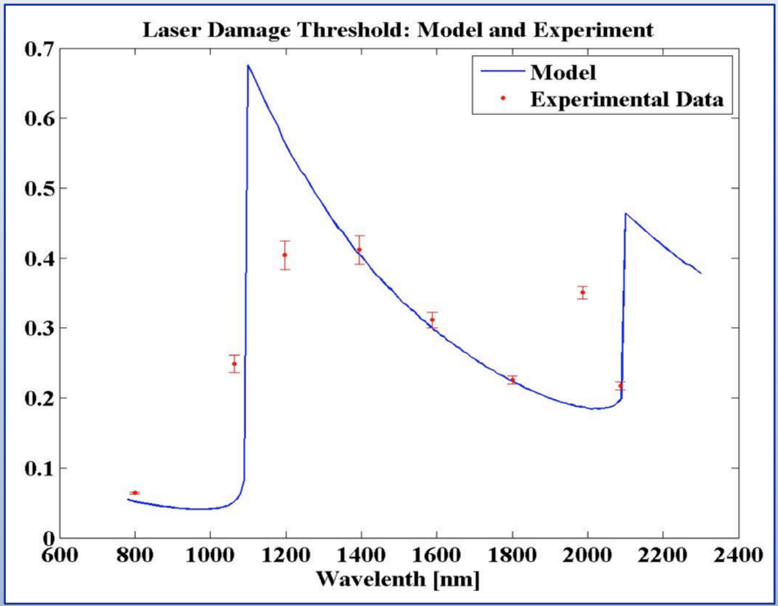
Breakdown mechanism

- Short pulse BD is different from ns regime

Pulse length (T)	~ few ps or shorter	10s of ps or longer
Ionization mechanism	Photoionization + avalanche	Avalanche
Energy transfer to lattice (phonons)	After the pulse	During the pulse
Damage mechanism	E-plasma absorption, ablation shock wave	Thermal damage (fracture, melting)
BD threshold (T)	~ flat	~ T^1/2
Surface quality	Not important	Very important
Multi-shot effects	Not important	Incubation (~x2)

SLAC data

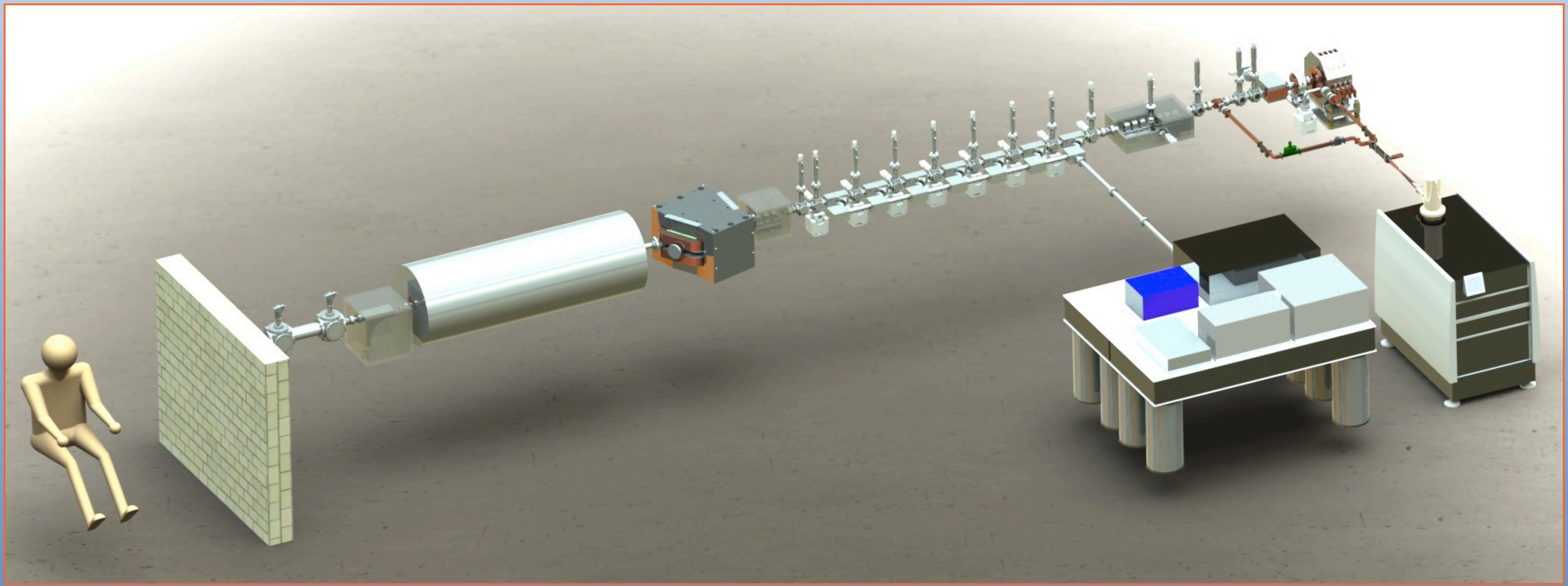
- Short pulse experimental data is very limited
- A study was conducted in 2011 at SLAC to study short pulse BD in 0.8-2.2 µm range (*K. Soong et al*)



Material	Thickness	Bandgap	F_{th} [J/cm^2]
Al_2O_3	1000μm	9.9eV	4.90$\pm$0.29
SiO_2 (Quartz)	1000μm	8.9eV	4.10$\pm$0.50
ZrO_2/Y_2O_3	15nm	5-7eV	3.97$\pm$0.16
HfO_2	<200nm	5.8eV	3.63$\pm$0.36
Si_3N_4	100nm	5.1eV	0.65$\pm$.05
Si	1000μm	1.1eV	0.14$\pm$.02

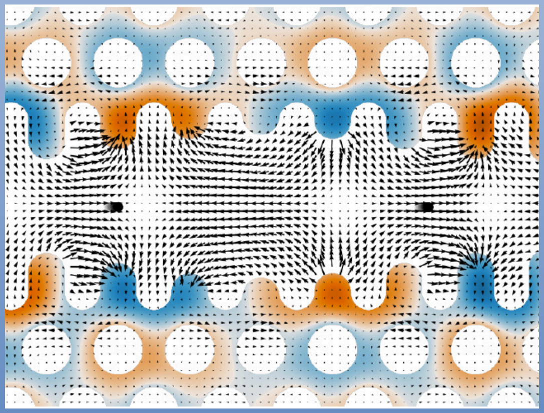
GALAXIE Project

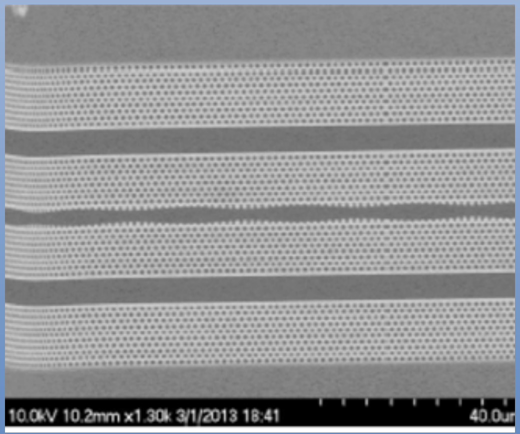
- DARPA funded project (RBT-UCLA-Stanford-PSU-BNL) to develop a room size hard X-ray FEL
- Based on mid-IR DLA @ 5.1 µm

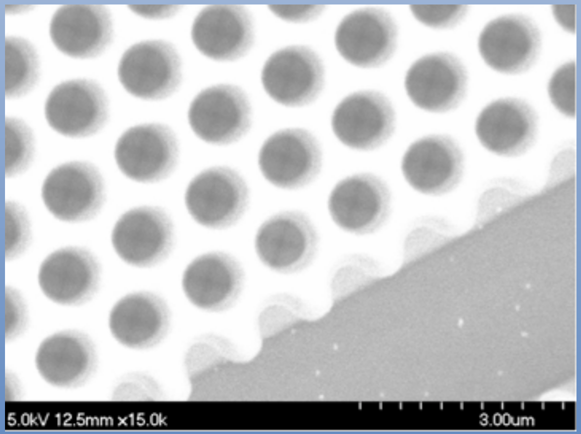


Mid-IR DLA (5.1 μm)

- Advantages of DLA at mid-IR:
  - Larger admittance and dynamic aperture
  - Smaller wakefields, higher beam loading
  - Favorable scaling of fabrication tolerances
  - 10 x ponderomotive potential at the same intensity (smaller Keldysh parameter, no MPI)
- Known disadvantage – additional laser R&D

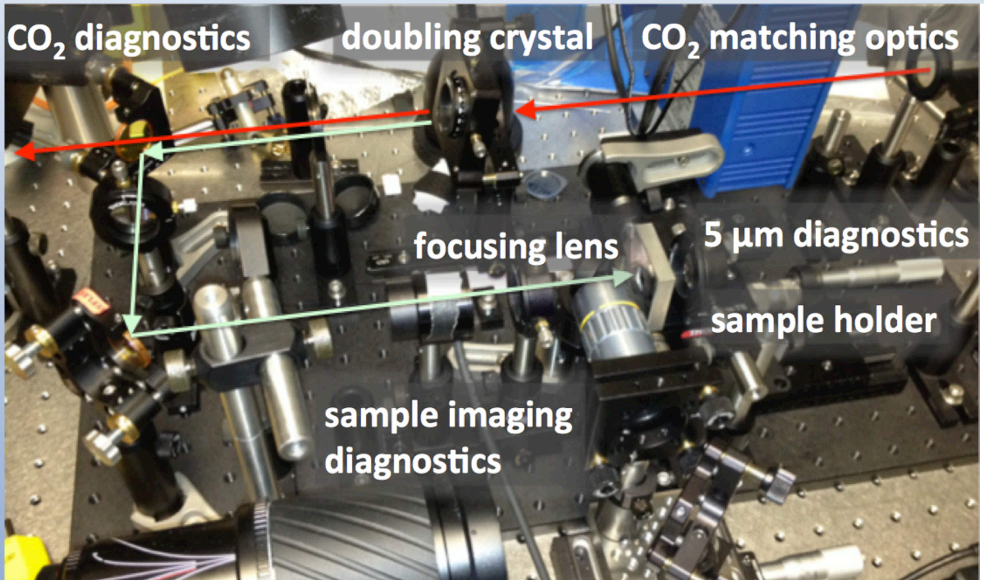


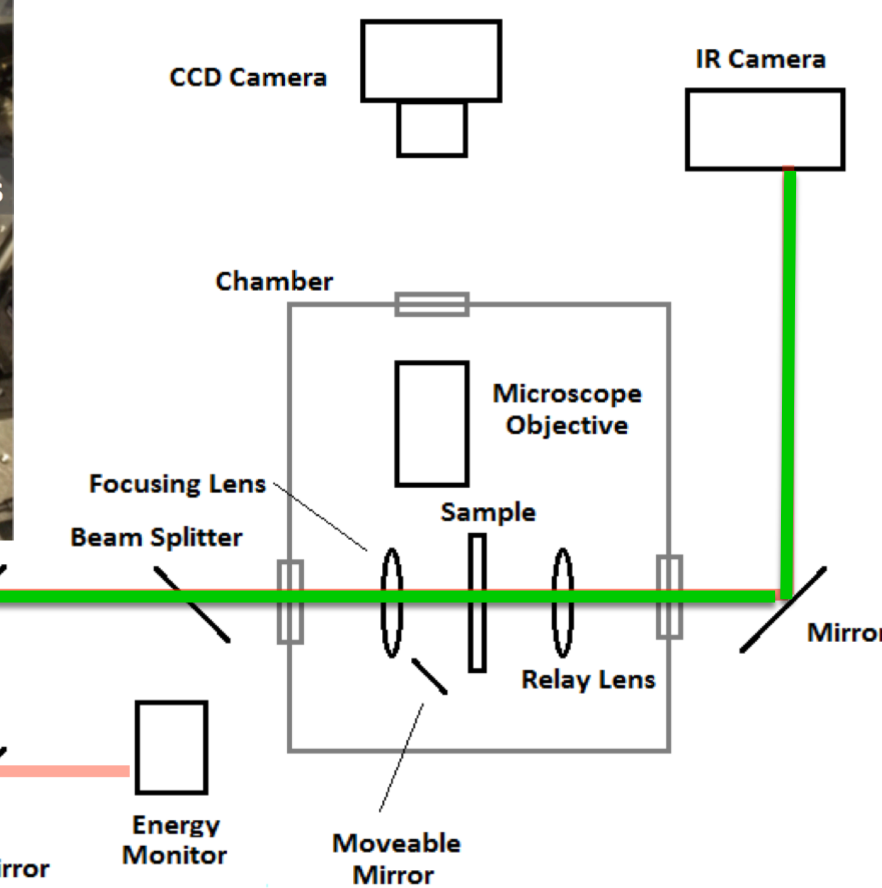




5 μm BD studies at BNL

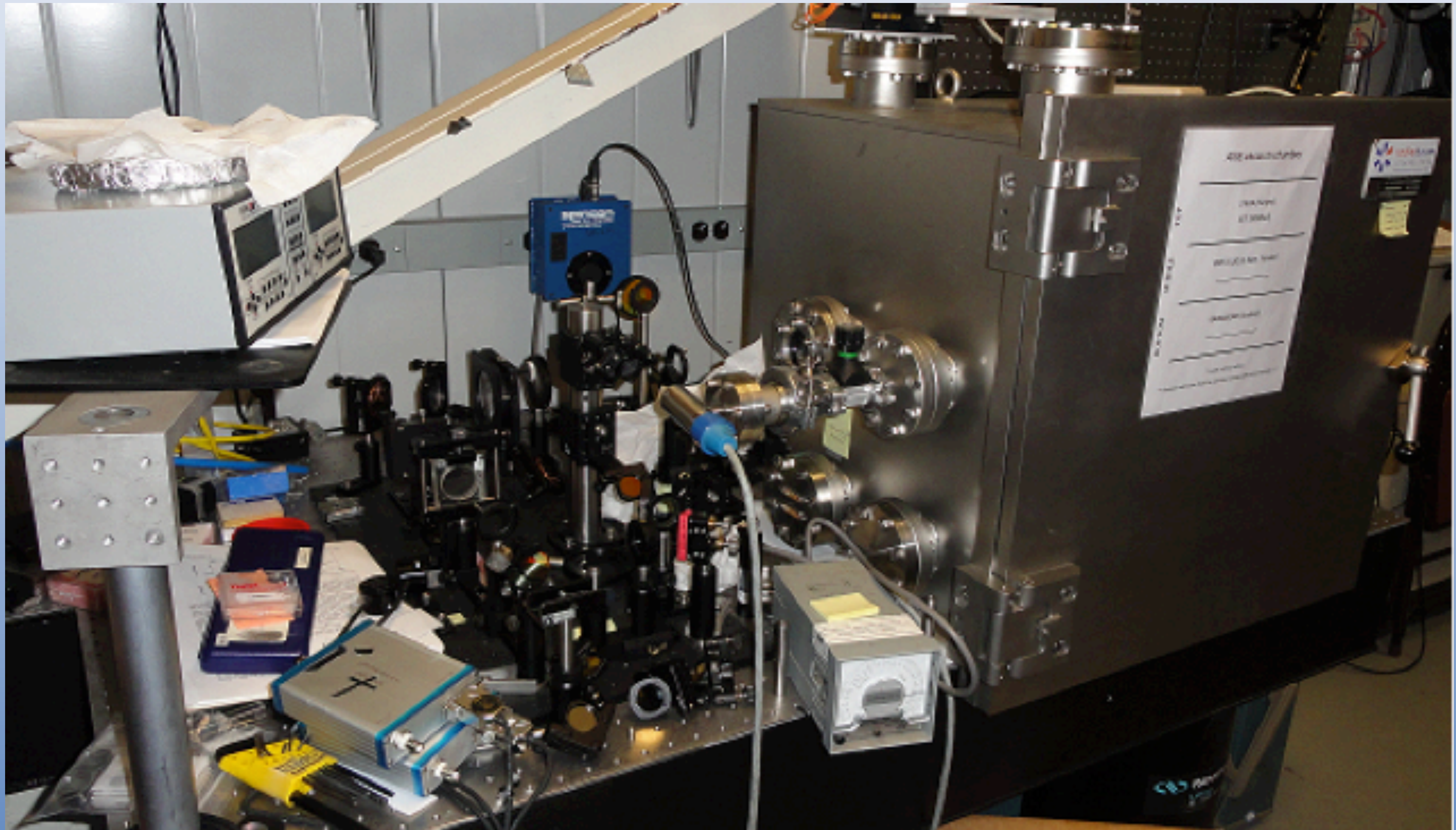
- There is no prior picosecond breakdown data at 5 μm



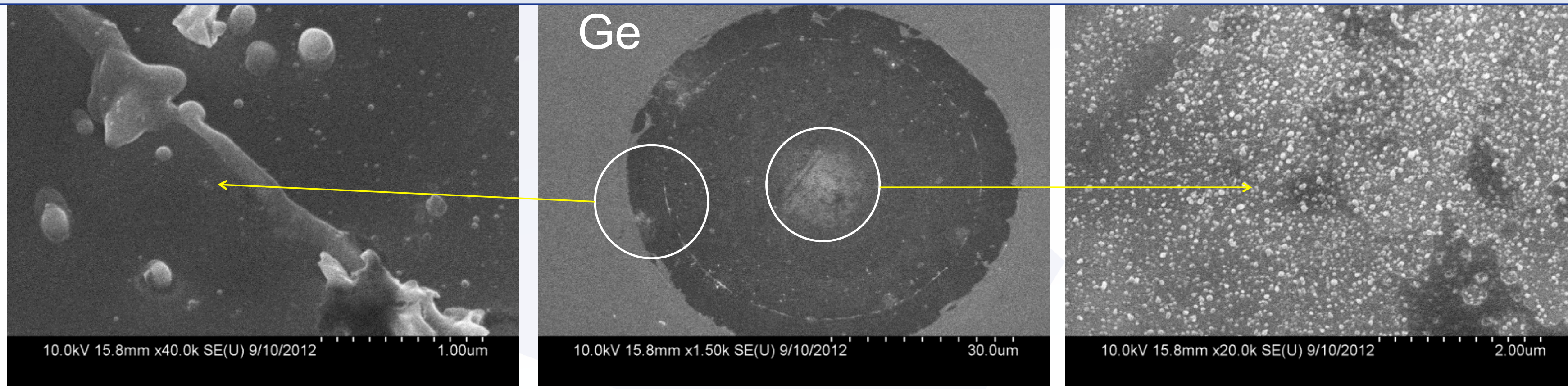


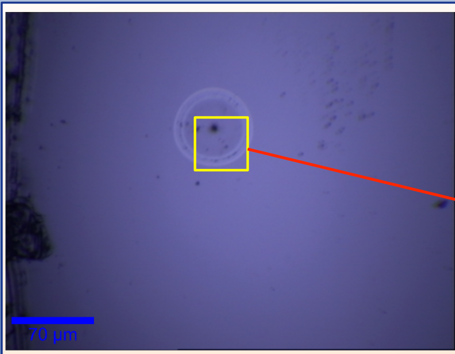
Air-evacuated set-up

- After initial data repeated experiment in vacuum

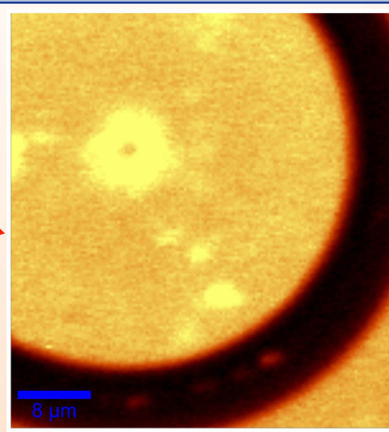


Results





Bright field image



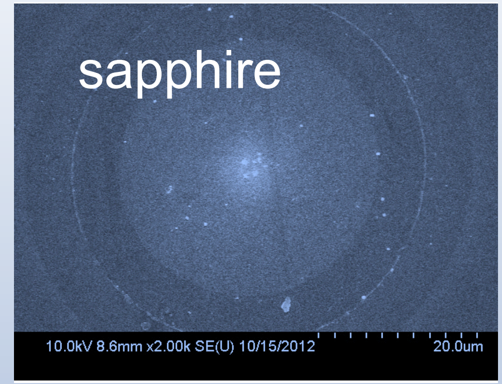
Raman microscopy

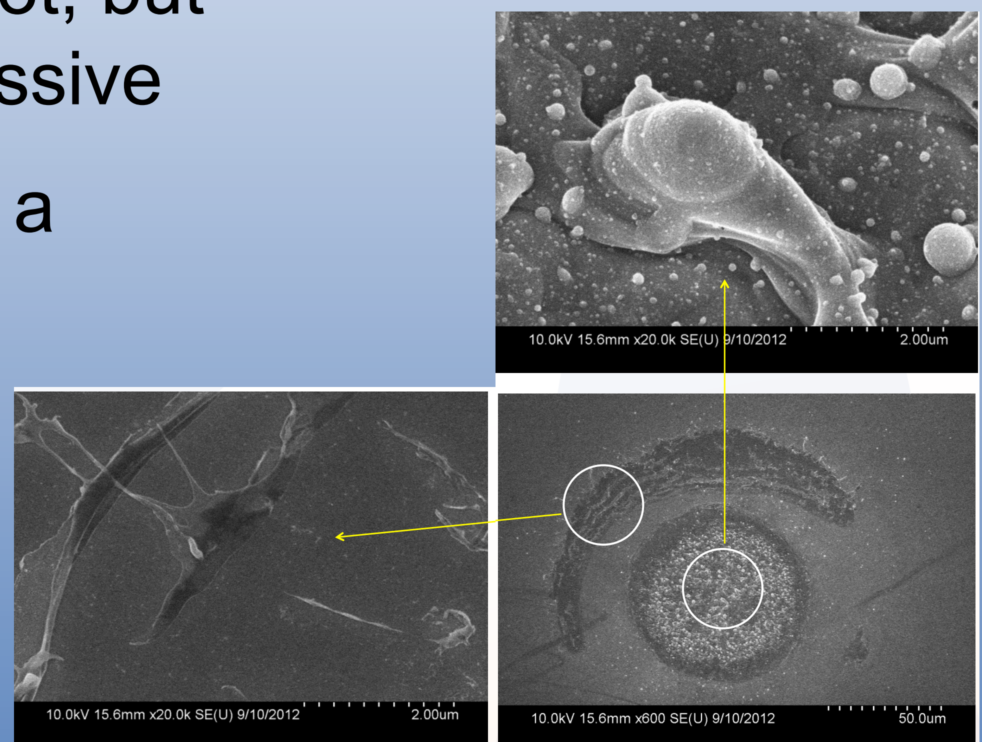
Raman intensity map using 521 cm^{-1} Si band

- Frozen surface wave rings and melting in the center

Results

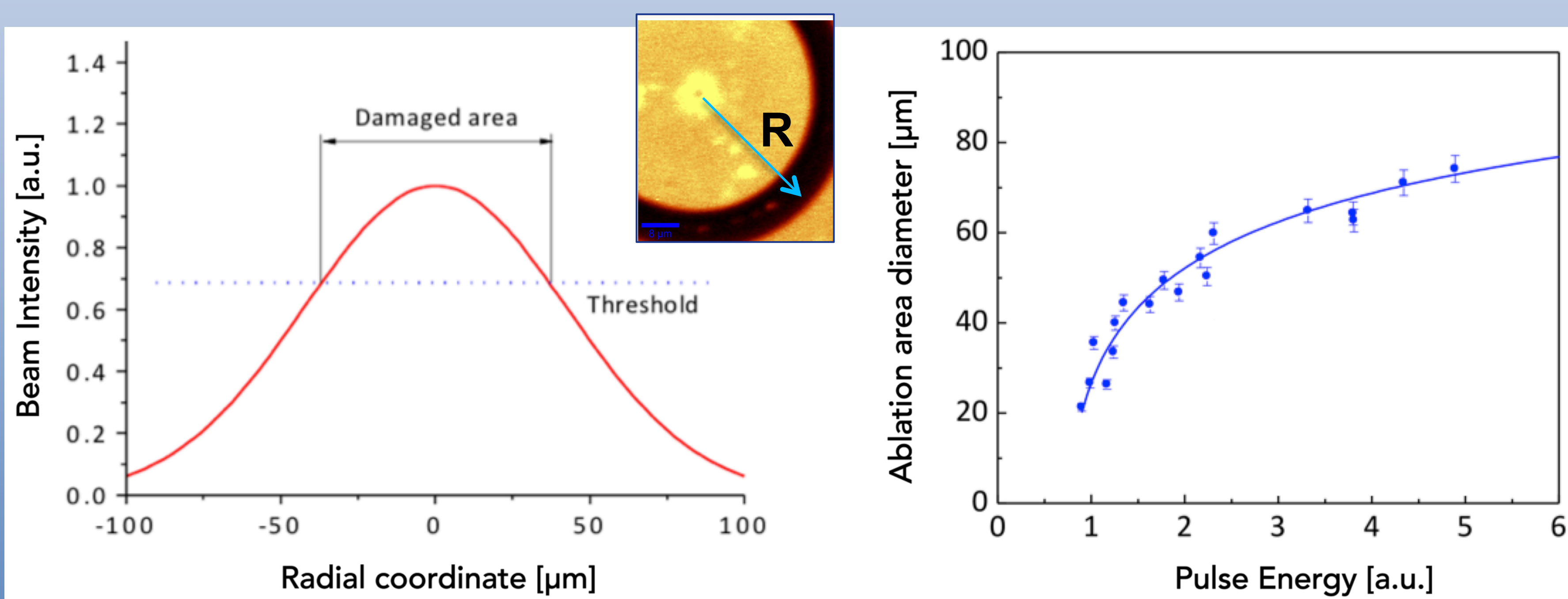
- Sapphire SEM shows similar pattern as Ge and Si.
- Multi-shot damage threshold is the same as single shot, but melting debris are massive
- Vacuum did not make a difference





Results

- The threshold damage was determined by approximating the ablation area diameter to zero
- The threshold value is well reproducible (characteristics of short pulse regime)



Results

- Consistent with SLAC results but larger (without MPI)

Material	Germanium	Silicon	Sapphire
Band Gap (eV)	0.67	1.1	9.9
Damage Threshold [J/cm²]	0.22 ± 0.02	0.29 ± 0.02	7.0 ± 0.3
Peak Fluence [J/cm²]	0.44	0.58	14.0

Material	Thickness	Bandgap	F_{th} [J/cm^2]
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2.3 GV/m @ 5 ps

Conclusion

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- We report the first measurements of picosecond OBD damage at 5 μm for Si, Ge and sapphire
- The damage threshold was well defined and above 800 nm data (possibly due to lack of MPI)
- At 5 ps laser pulses the damage pattern was that of a short pulse regime
- Characteristic band gap dependence was observed with sapphire showing that it can support pulsed energies up to 7 J/cm^2